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A Compact High Field Magnet System for Medical Applications

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Abstract. High magnetic field gradients can be used for various medical applications including magnetically targeted drug delivery, magnetic cell separation and controlled local heating for the ablation of tumours. These processes involve the use of biocompatible magnetic nanoparticles directed to the area of interest by the use of a field gradient. The force on the nanoparticle is proportional to the field gradient product, so high fields are required for effective delivery. Bulk superconductors are an attractive solution for both drug delivery and the next generation of low cost magnetic resonance imaging magnets. In particular, MgB_2 is seen as an attractive material due to its low cost, simple processing and relatively high transition temperature (~39 K).
This paper describes the development of a breadboard compact delivery system suitable for medical applications. This incorporates a cryogenic stage which utilises long life space-proven technology and state of the art ex-situ processed MgB_2 pellets.

1. Introduction

High magnetic fields have uses in a clinical environment for Magnetic Resonance Imaging (MRI), but there is also increasing interest in other areas, including targeted drug delivery, magnetic cell separation and thermal ablation for treating cancerous tumours. Dense pellets of bulk superconducting material can have high critical currents enabling them to generate intense magnetic fields. There are three main challenges in the use of these materials: the requirement to keep them below the superconducting transition temperature, the charging process required to magnetise them and the need to keep the distance from the pellet to the patient as short as possible. An attractive material for the bulk superconductor is

Figure 1. 50 mm diameter MgB_2 hot pressed bulk superconductor.

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MgB_2, which is cheap, relatively easy to process and has a relatively high transition temperature of approximately 39 K.

The cryogenic system detailed here is based around a compressor design previously used for the 4 K cooler on the Planck spacecraft [1]. This is combined with Additively Manufactured (AM) heat exchangers and liquid pot to produce a compact, very long life system with zero maintenance that could be developed further for use in a clinical environment.

2. System Design and Configuration

The system layout is shown in figure 2 and is based around a Joule-Thomson (JT) cooler using neon as the working fluid. Two stages of compression are used to compress the gas from around 1.5 bar to 9 bar.

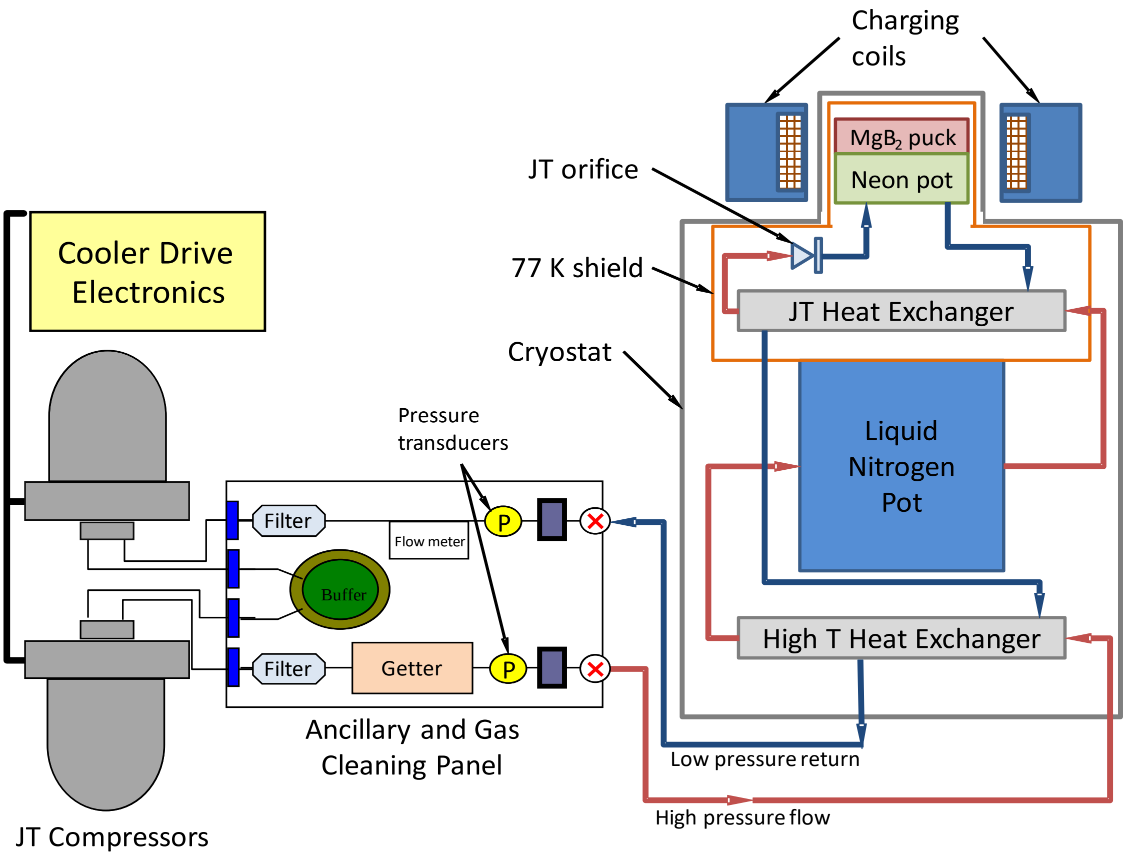

Figure 2. System schematic showing compressors and ancillary panel (left) and cryostat (right).

2.1. Compressors and Ancillary Panel

The compressors are reciprocating type with loudspeaker drive and a flexure spring suspension system. Reed valves in the compressor head produce the required high and low pressures for the JT system. They are similar to the ones used on the Planck spacecraft.

The compressed gas is cleaned by passing it through a commercially available getter. This is accommodated on an ancillary panel (see figure 2) adjacent to the compressors, which also includes provision for pressure and mass-flow measurement.

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2.2. Cryostat Design

The MgB_2 puck is contained in a bespoke, vacuum insulated cryostat (see figure 2 and figure 4). The cryostat also incorporates the liquid nitrogen vessel for pre-cooling, the heat exchangers and the pot for containing the liquid neon. High pressure neon enters the cryostat from the compressors/ancillary panel and flows into the high pressure side of a counter-current heat exchanger. This makes use of the enthalpy from the cold return gas to cool the incoming warm stream. On exiting this heat exchanger, the neon is cooled in a liquid nitrogen bath to 77 K before entering the JT heat exchanger. After the gas is expanded through a fine nozzle (the JT orifice), the two-phase flow enters the liquid pot at the cold end. The MgB_2 puck is glued to the flat part of the pot and has a large heat transfer area. Radiation shields are employed to intercept heat from the inner surfaces of the vacuum vessel by utilising the cooling at 77 K available from the liquid nitrogen pot.

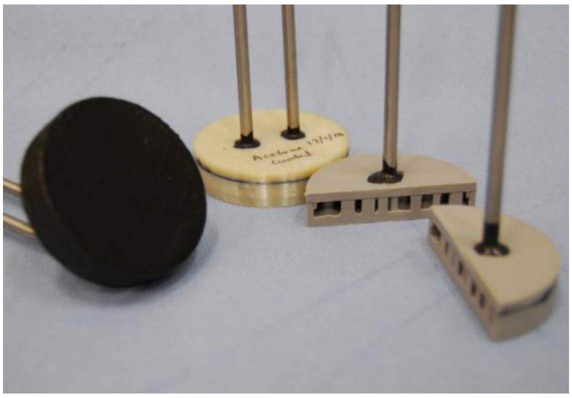

Figure 3. Neon pots – 50 mm diameter.

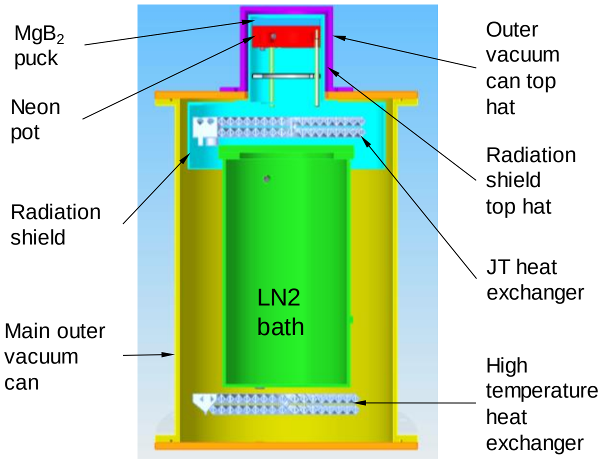

Figure 4. Cross-section of the cryostat.

A CAD image of the cryostat cross section is shown in figure 4. The height of the system as drawn is 330 mm. The volume of the liquid nitrogen pot is sized so that it only requires filling once a day. The neon pot (figure 3) is made by Additive Manufacturing (AM). This is to minimise the eddy current heating that would occur during the charging process. The pot has been made from Ultem (a high strength plastic) and the more standard Verogray [2]. The main issue with the manufacture was the porosity of the printed plastic. This was overcome by coating the pot with a thin layer of epoxy resin. The pots were ultimately leak tight and able to withstand pressures in excess of 20 bar without failure.

Eddy currents generated during ramping of the charging coils in the radiation shield top hat (see figure 4) have been modelled using Opera software. The power loss due to eddy current heating in the radiation shield top hat is shown in figure 5(a). Two geometries are considered: the baseline design and a slotted geometry, shown in figure 5(b) and (c), respectively. In the baseline design, 300 J is deposited in the radiation shield top hat when the charging coil is powered, causing a temperature rise of 20 K. If two slots are included in the design, the temperature rise is reduced to < 6 K as the path of the eddy currents is disrupted.

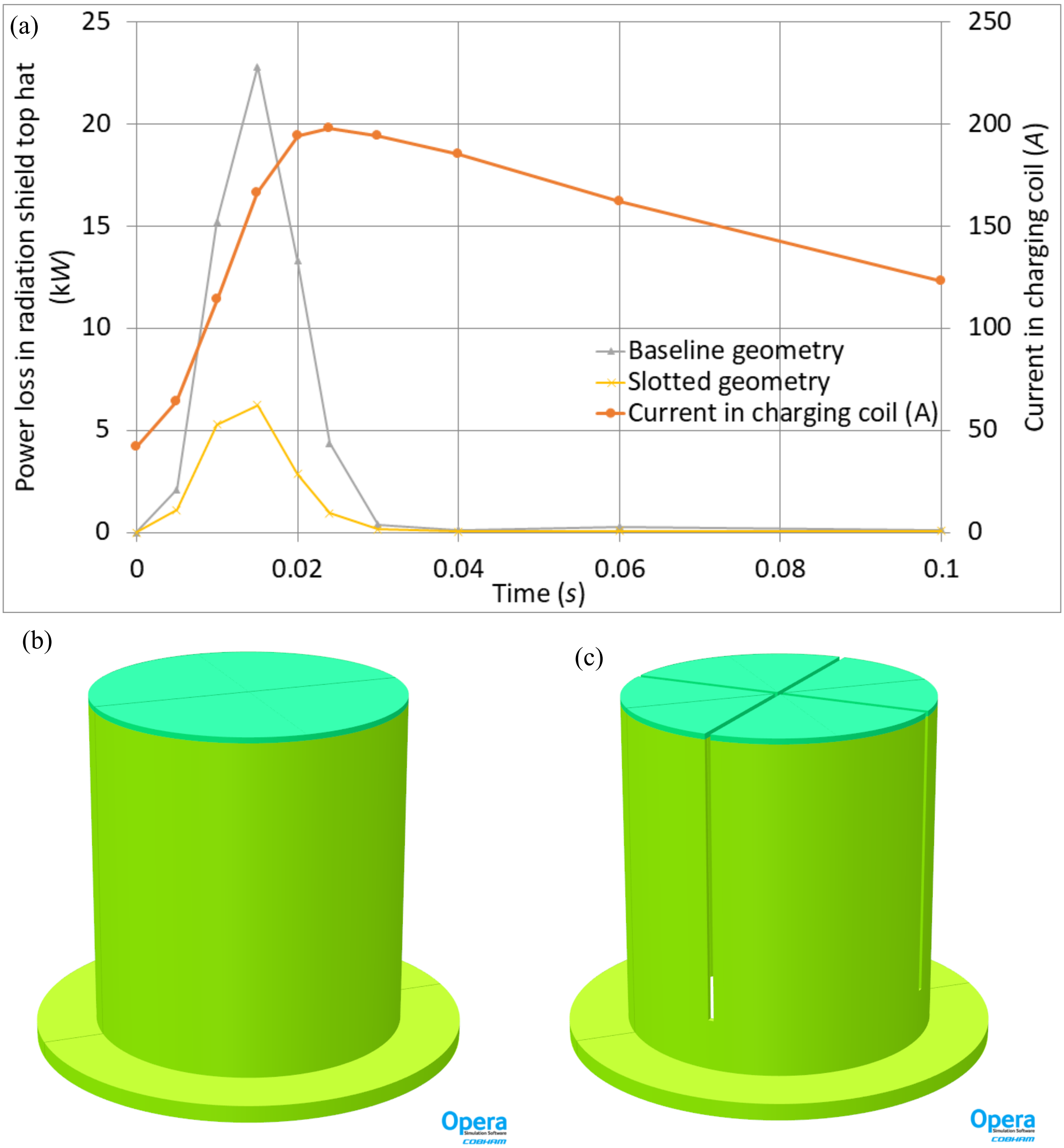

Figure 5. (a) Power dissipated by eddy currents in the top-hat radiation shield during charging of the MgB_2 puck for both a simple continuous shield (b) and a slotted version (c).

3. Charging Coil Design and Test

Once the puck is cold, it is energised by use of a solenoid cooled to liquid nitrogen temperatures. The solenoid fits over the cold end with its own custom dewar. This solenoid is pulsed with a large current and this magnetises the MgB_2 puck. With the prototype solenoid and the charging system developed at Cambridge University pulses in excess of 5 T have been achieved (see figure 6).

4. Heat Exchanger Design and Manufacture

The heat exchangers for the system are manufactured using AM processes (Direct Laser Metal Sintering); a prototype is shown in figure 7. The flow channels inside the heat exchanger are profiled to allow for the AM process. The material for the prototype uses 304 stainless steel. The heat exchanger is a counter-current type and an active length of 3.2 m has been achieved in a compact configuration. This has been pressure and leak tested with no issues. The heat exchanger has been designed to work well with the typical operating parameters of the compressors: typically a high pressure of ~9 bar, a low pressure of ~1.5 bar and a mass flow of ~30 mg/s.

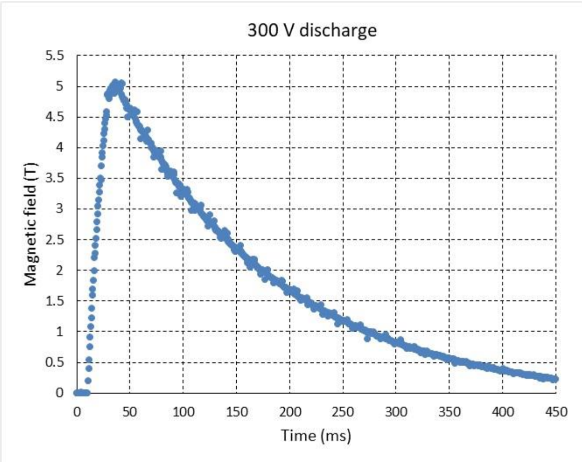

Figure 6. Field measured inside a prototype charging solenoid during pulsing.

Figure 7. Additively Manufactured prototype spiral heat exchanger.

5. Future work

The basic design of the system is complete and most of the components breadboarded and, in some cases, tested. The manufacture is due to be completed in early 2019, with system testing following immediately afterwards. Further AM produced heat exchanger configurations will be pursued. To date, there were no issues with leaks or porosities on the metal printed components. Trials will be made with various MgB_2 pucks, with the possibility to extend to other materials once the system is proven. The test programme will include cryogenic performance tests, field measurements and trials with magnetic nanoparticles.

6. References

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Acknowledgements

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